

Cosmological and Astrophysical Constraints on Tensor Unparticles

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Abstract

We calculate cosmological and astrophysical bounds on the couplings between standard model fields and tensor unparticles. The present day density of tensor unparticles from neutrino-neutrino and photon-photon annihilation is calculated. Also, the supernovae volume energy loss rates from electron-positron and photon-photon annihilation to tensor unparticles are calculated. The constraints from matter density and supernovae volume energy loss rates from photon-photon annihilation are on the same order of magnitude, while the bounds from supernovae volume energy loss rates from electron-positron annihilation are an order of magnitude lower. We find the couplings between standard model fields and tensor unparticles are at least an order of magnitude lower than those used for previous studies of tensor unparticle collider phenomenology.

I. INTRODUCTION

Recently Georgi [1, 2] has introduced the idea of a low energy theory where a scale-invariant sector couples to the standard model. At high energies a theory with a non-trivial infrared fixed point couples to the standard model via particles with mass M_U . Below M_U the non-renormalizable interaction is

$$\frac{1}{M_U^k} O_{SM} O_{\mathcal{BZ}}, \quad (1)$$

where $k = n + d_{\mathcal{BZ}} - 4$, n is the scale dimension of the standard model operator O_{SM} , and $d_{\mathcal{BZ}}$ is the scale dimension of the operator $O_{\mathcal{BZ}}$, labeled \mathcal{BZ} for Banks-Zaks [3]. Since the mediating particles have not been observed, we expect their masses, M_U , to be larger than 1 TeV.

The scale invariance of the Banks-Zaks operator sets in at a scale Λ_U . At energies below Λ_U , the conformal sector couples to the standard model through the non-renormalizable interactions

$$C_U \frac{\Lambda_U^{d_{\mathcal{BZ}} - d_U}}{M_U^k} O_{SM} O_U \equiv \frac{\kappa_U}{\Lambda_U^{d_U + n - 4}} O_{SM} O_U, \quad \kappa_U = C_U \left(\frac{\Lambda_U}{M_U} \right)^k \quad (2)$$

where d_U is the dimension of the unparticle operator O_U , and C_U are dimensionless constants set by matching Eqs. (1) and (2) below the conformal scale Λ_U . In principle C_U can be different for each standard model operator, but we expect them to be on the order of 1. For the unparticles to be relevant at future colliders, such as the LHC, Λ_U should be at least a few 100 GeV.

If the unparticle sector is to be scale invariant, its fields cannot have definite non-zero mass. Hence, their spectral density function is different than that of ordinary particles. Demanding that the matrix element $\langle 0 | O_U(x) O_U^\dagger(0) | 0 \rangle$ be scale invariant and have scaling dimension $2d_U$, the spectral density function of unparticles is found to be [1]

$$\rho(P_U^2) = A_{d_U} \theta(P_U^0) \theta(P_U^2) (P_U^2)^{d_U - 2}, \quad (3)$$

where, by convention,

$$A_{d_{\mathcal{U}}} = \frac{16\pi^{5/2}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}} + 1/2)}{\Gamma(d_{\mathcal{U}} - 2)\Gamma(2d_{\mathcal{U}})}. \quad (4)$$

There has been much recent interest in the phenomenological [4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52], astrophysical [53, 54, 55], long-range force [55, 56, 57, 58], and cosmological [59, 60] implications of unparticle physics.

In this paper we look at the limits on the couplings between standard model fields and tensor unparticles from cosmology and astrophysics. In Section II we present effective interactions between tensor unparticles and standard model fields and outline the deconstruction of unparticles. The present day tensor unparticle density is calculated and matter density constraints are placed on the tensor unparticle and standard model couplings in Section III. In Section IV, the supernovae volume energy loss rates from photon-photon and electron-positron annihilation to tensor unparticles is calculated and constraints from SN1987A are placed on the tensor unparticle and standard model couplings. A summary of results and the conclusions are given in Section V.

II. THE MODEL

The effective standard model and tensor unparticle interactions under study are [24]

$$\frac{\kappa_{\gamma}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} F_{\mu\beta} F_{\nu}^{\beta} O_{\mathcal{U}}^{\mu\nu}, \quad -\frac{1}{4} \frac{\kappa_f}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{\psi}_f i(\gamma_{\mu} \overleftrightarrow{D}_{\nu} + \gamma_{\nu} \overleftrightarrow{D}_{\mu}) \psi_f O_{\mathcal{U}}^{\mu\nu}, \quad (5)$$

where $F^{\mu\nu}$ is the photon field strength operator, ψ_f is a fermion field, and $O_{\mathcal{U}}^{\mu\nu}$ is the tensor unparticle operator.

Following the method in [61], we break the conformal invariance of the unparticle by decomposing it into fields $\lambda_j^{\mu\nu}$ with masses

$$M_j^2 = \Delta^2 j, \quad (6)$$

where Δ is some mass gap. As $\Delta \rightarrow 0$, the mass spectrum of the λ_j 's becomes continuous. This limit is the conformal limit.

Now we rewrite the unparticle operator as $O_{\mathcal{U}}^{\mu\nu} = \sum_j F_j \lambda_j^{\mu\nu}$. By matching the correlation functions of the scale-invariant unparticle to that of the deconstructed unparticle in the

conformal limit, it can be found that

$$F_j^2 = \frac{A_{d_{\mathcal{U}}}}{2\pi} \Delta^2 (M_j^2)^{d_{\mathcal{U}}-2}. \quad (7)$$

The interactions in Eq. (5) then become

$$\frac{\kappa_\gamma}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} F_{\mu\beta} F_\nu^\beta \sum_j F_j \lambda_j^{\mu\nu}, \quad -\frac{1}{4} \frac{\kappa_f}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}} \bar{\psi}_f i(\gamma_\mu \overleftrightarrow{D}_\nu + \gamma_\nu \overleftrightarrow{D}_\mu) \psi_f \sum_j F_j \lambda_j^{\mu\nu}. \quad (8)$$

Hence, the Feynman rules for the fields $\lambda_j^{\mu\nu}$ are the same as those found in [24] for $O_{\mathcal{U}}^{\mu\nu}$ multiplied by F_j .

III. CRITICAL DENSITY BOUNDS

Since $F_j \rightarrow 0$ in the conformal limit, each individual deconstructing particle field, λ_j , decouples from the standard model. In processes mediated by unparticles or in which an unparticle is produced, the number of available intermediate or final state particles, λ_j , increases to compensate for the decoupling. For the decay of an unparticle to standard model particles, the number of available final state particles does not increase to compensate for the decoupling. Hence the unparticle does not decay to standard model particles [61]. If unparticles are produced abundantly in early times, they could overclose the universe.

In standard cosmology, Big Bang Nucleosynthesis (BBN) explains the abundance of the light elements. For unparticles not to interfere with BBN, they must freeze out at a temperature, T_* , greater than the temperature of BBN, 1 MeV. If T_* is too large, an overabundance of unparticles could have been produced in the early universe. Conservatively, we assume $T_* = 1$ MeV.

We will now calculate the present day density of unparticles. A similar calculation was previously done for Kaluza Klein gravitons in large extra-dimensions [62]. First, the contribution from single flavor neutrino-neutrino annihilation is calculated. The spin averaged matrix element for $\nu\nu \rightarrow \lambda_j$ is

$$\overline{\sum} |\mathcal{M}|^2 = \kappa_\nu^2 \frac{F_j^2}{16} \frac{s^2}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}, \quad (9)$$

where s is the center of mass energy squared for the process.

The evolution of the number density of the field λ_j is described by the Boltzmann equation:

$$\dot{n}^{(j)} + 3n^{(j)}H = \int \frac{d^3\mathbf{p}_\nu}{(2\pi)^3 2|\mathbf{p}_\nu|} \frac{d^3\mathbf{p}_{\bar{\nu}}}{(2\pi)^3 2|\mathbf{p}_{\bar{\nu}}|} \frac{d^3\mathbf{p}_j}{(2\pi)^3 2\sqrt{\mathbf{p}_j^2 + M_j^2}} \quad (10)$$

$$\times (2\pi)^4 \delta^4(p_j - p_\nu - p_{\bar{\nu}}) \overline{\sum} |\mathcal{M}|^2 e^{-|\mathbf{p}_\nu|/T} e^{-|\mathbf{p}_{\bar{\nu}}|/T} \quad (11)$$

Integrating the Boltzmann equation, it is found that

$$s\dot{Y}^{(j)} = \dot{n}^{(j)} + 3n^{(j)}H = \kappa_\nu^2 \frac{M_j^5 T F_j^2}{512\pi^3 \Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \mathcal{K}_1\left(\frac{M_j}{T}\right), \quad (12)$$

where \mathcal{K}_1 is a Bessel function of the second kind. The conservation of entropy was used to rewrite the Boltzmann equation in terms of the variable $Y_j = n_j/s$, where s is entropy density.

The temperature, T , of radiation and time, t , are related by [63]

$$t = 0.301 g_*^{-1/2} \frac{M_{pl}}{T^2}, \quad (13)$$

where M_{pl} is the Planck mass. Since we are interested in times after unparticles freeze out, the relativistic degrees of freedom are $g_* = 10.75$. Using that the entropy density is proportional to T^3 , the present-day number density of λ_j from single flavor neutrino annihilation is found to be

$$n_o^{(j)} = 1.1 \times 10^{-5} \kappa_\nu^2 T_0^3 M_{pl} \frac{M_j F_j^2}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \int_{M_k/T_*}^{\infty} dx x^3 \mathcal{K}_1(x) \quad (14)$$

where $T_0 = 1.96$ K is the current temperature of neutrinos.

The states λ_j can also be produced by photon-photon annihilation. For simplicity we assume the dimensionless coupling constants κ_ν and κ_γ are equal and relabel them as κ . The spin averaged matrix element squared for $\gamma\gamma \rightarrow \lambda_j$ is

$$\overline{\sum} |\mathcal{M}|^2 = \kappa^2 \frac{F_j^2}{2} \frac{s^2}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}. \quad (15)$$

$d_{\mathcal{U}}$	4/3	3/2	5/3	2
(a) $\rho_{\mathcal{U}}$	$5.9 \times 10^{-39} \kappa^2 \Lambda_{\mathcal{U}}^{-8/3}$	$6.1 \times 10^{-41} \kappa^2 \Lambda_{\mathcal{U}}^{-3}$	$5.6 \times 10^{-43} \kappa^2 \Lambda_{\mathcal{U}}^{-10/3}$	$3.7 \times 10^{-47} \kappa^2 \Lambda_{\mathcal{U}}^{-4}$
(b) $\Lambda_{\mathcal{U}} >$	$1.9 \times 10^3 \kappa^{3/4}$	$180 \kappa^{2/3}$	$26 \kappa^{3/5}$	$1.4 \kappa^{1/2}$

TABLE I: (a) The present day density of tensor unparticles from neutrino-neutrino and photon-photon annihilation in units of GeV^4 , where $\Lambda_{\mathcal{U}}$ has been normalized to 1 TeV, and (b) lower bounds on $\Lambda_{\mathcal{U}}$ in units of TeV for a variety $d_{\mathcal{U}}$ values.

There is also a symmetry factor of 1/2 from initial state photons. Hence, the photon-photon annihilation contribution to the number density of tensor unparticles will be four times that of the single flavor neutrino-neutrino annihilation contribution.

To find the present day density of tensor unparticles, it will be necessary to sum over all the states λ_j and take the conformal limit. From Eq. (6), we see that summing over all states is equivalent to integrating the results for a single field λ_j over the measure

$$dn = dM_n^2 / \Delta^2. \quad (16)$$

Considering all three flavors of neutrino, the present day density of unparticles from neutrino-neutrino and photon-photon annihilation is

$$\rho_{\mathcal{U}} = \frac{14}{\Delta^2} \int_0^\infty dM_j M_j^2 n_0^{(j)} \quad (17)$$

$$= 2.6 \times 10^{-5} \kappa^2 A_{d_{\mathcal{U}}} M_{pl}^2 T_0^3 \left(\frac{T_*}{\Lambda_{\mathcal{U}}} \right)^{2d_{\mathcal{U}}} \int_0^\infty dy y^{2d_{\mathcal{U}}-1} \int_y^\infty dx x^3 \mathcal{K}_1(x), \quad (18)$$

where we have substituted for F_j . Note that since $F_j^2 \propto \Delta^2$ and $dn \propto \Delta^{-2}$, the density of unparticles does not depend on the mass gap. The results of the density of tensor unparticles for $d_{\mathcal{U}} = 4/3, 3/2, 5/3$, and 2 are given in Table I (a).

For tensor unparticles not to overclose the universe, their present day density must be less than the matter density of the universe, $\rho_m = 1.028 \times 10^{-47} \text{ GeV}^4$. Using this constraint, bounds on $\Lambda_{\mathcal{U}}$ and κ can be found. These bounds are given in Table I (b) for $d_{\mathcal{U}} = 4/3, 3/2, 5/3$, and 2.

The cosmology of scalar and vector unparticles has been studied before [59, 60]. We now compare these results to our results for tensor unparticles.

In [60], the effects on BBN from quark decay to scalar unparticles was studied. It was found that in order for scalar unparticles not to interfere with BBN, $M_{\mathcal{U}} \gtrsim 20 - 2600$ TeV for $1.1 \leq d_{\mathcal{U}} \leq 2$, $2 \leq d_{\mathcal{BZ}} \leq 4$, $\Lambda_{\mathcal{U}} \gtrsim 1$ TeV, and $A_{d_{\mathcal{U}}} C_{\mathcal{U}}^2 \sim 1$. Using these parameter values and the definition of $\kappa_{\mathcal{U}}$ in Eq. (2), for tensor unparticles we find the less stringent condition that $M_{\mathcal{U}} \gtrsim 1.8 - 180$ TeV for $4/3 \leq d_{\mathcal{U}} \leq 2$. The lowest bound came from $d_{\mathcal{U}} = 2$ and $k = 4$ and the highest bound came from $d_{\mathcal{U}} = 4/3$ and $k = 2$.

The effect of vector unparticles on BBN was studied in [59]. With $k = 2$, $M_{\mathcal{U}} = 1000$ TeV, and $|C_{\mathcal{U}}| = 1$, it was found that $\Lambda_{\mathcal{U}} \lesssim 100$ GeV for $d_{\mathcal{U}} = 3/2$ and 2. There were no limits given for $d_{\mathcal{U}} = 4/3$ or $5/3$. For $k = d_{\mathcal{U}} = 2$ there is no tensor unparticle density limit on $\Lambda_{\mathcal{U}}$, only a lower bound on $M_{\mathcal{U}}$. For $d_{\mathcal{U}} = 3/2$ we find that $\Lambda_{\mathcal{U}} \lesssim 1.7 \times 10^5$ TeV. That is, under these assumptions we do not have a bound for $\Lambda_{\mathcal{U}}$.

IV. SUPERNOVAE ENERGY LOSS RATES

Data from IMB and Kamiokande indicates that in a period on the order of 10 seconds the neutrino flux from SN1987A carried away more than 2×10^{53} ergs of energy. The energy released due to the core collapse to a neutron star is $\sim 3 \times 10^{53}$ ergs, hence neutrinos carry away most of this energy. This places a constraint on the supernovae energy loss rate from new physics. For a report on the classic example of supernovae energy losses through axions see [64]. There have also been many studies of energy losses due to KK gravitons [65, 66, 67, 68, 69, 70, 71, 72].

Since unparticles have a continuous mass spectrum, they can be produced in supernovae. If the energy loss due to unparticles is excessive it can change stellar evolution. Here we calculate the supernovae volume energy loss rates (emissivities) resulting from emission of tensor unparticles in photon-photon and electron-positron annihilation, and place constraints on $\Lambda_{\mathcal{U}}$ and the relevant dimensionless coupling constant.

A. Photon-Photon annihilation

First we consider the photon-photon annihilation to tensors unparticles. Using the Feynman rules derived in [24], we obtain the spin-averaged cross section for $\gamma\gamma \rightarrow \lambda_j$,

$$\sigma_{\gamma\gamma}^j(s) = C_\gamma^2 \frac{A_{d_{\mathcal{U}}}}{8} \frac{\Delta^2(M_j^2)^{d_{\mathcal{U}}-1}}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \delta(s - M_j^2), \quad (19)$$

where s is the squared center of mass energy.

The supernova volume emissivity is found by thermally averaging over the Bose-Einstein distribution,

$$Q_\gamma^j = \int \frac{2d^3\mathbf{k}_1}{(2\pi)^3} \frac{1}{e^{\omega_1/T} - 1} \int \frac{2d^3\mathbf{k}_2}{(2\pi)^3} \frac{1}{e^{\omega_2/T} - 1} \frac{s(\omega_1 + \omega_2)}{2\omega_1\omega_2} \sigma_{\gamma\gamma}^j, \quad (20)$$

where T is the supernova temperature. The center of mass energy squared in terms of the photon energies and opening angle, $\theta_{\gamma\gamma}$, is

$$s = 2\omega_1\omega_2(1 - \cos\theta_{\gamma\gamma}) \quad (21)$$

To find the volume emissivity from tensor unparticles, we need to sum over the states λ_j using the measure in Eq. (16). After carrying out the integral and summing over states, the supernova volume emissivity from photon-photon annihilation to tensor unparticles is

$$Q_\gamma = \zeta(d_{\mathcal{U}} + 2)\Gamma(d_{\mathcal{U}} + 2)\zeta(d_{\mathcal{U}} + 3)\Gamma(d_{\mathcal{U}} + 3)\kappa_\gamma^2 \frac{A_{d_{\mathcal{U}}}4^{d_{\mathcal{U}}-1}}{2\pi^4(d_{\mathcal{U}} + 1)} \frac{T^{2d_{\mathcal{U}}+5}}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}. \quad (22)$$

Plasma effects which may change the photon dispersion relations away from those of free particles [64] have been neglected.

B. Electron Positron Annihilation

In calculating the electron-positron annihilation cross section, we neglect the electron mass since $m_e \ll T_{SN} \sim 30$ MeV, the benchmark supernova temperature. The spin averaged cross section for electron positron annihilation to λ_j is

$$\sigma_{e^+e^-}^j(s) = \kappa_e^2 \frac{A_{d_{\mathcal{U}}}}{16} \frac{\Delta^2(M_j^2)^{d_{\mathcal{U}}-1}}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}} \delta(s - M_j^2) \quad (23)$$

The supernova volume emissivity from the electron-positron annihilation to tensor unparticles is found by thermally averaging over the Fermi-Dirac distribution,

$d_{\mathcal{U}}$	4/3	3/2	5/3	2
(a) Q_{γ}	$3.6 \times 10^{41} \kappa_{\gamma}^2 \Lambda_{\mathcal{U}}^{-8/3}$	$1.2 \times 10^{40} \kappa_{\gamma}^2 \Lambda_{\mathcal{U}}^{-3}$	$73.8 \times 10^{38} \kappa_{\gamma}^2 \Lambda_{\mathcal{U}}^{-10/3}$	$2.7 \times 10^{35} \kappa_{\gamma}^2 \Lambda_{\mathcal{U}}^{-4}$
(b) Q_e	$1.2 \times 10^{39} \kappa_e^2 \Lambda_{\mathcal{U}}^{-8/3}$	$4.9 \times 10^{37} \kappa_e^2 \Lambda_{\mathcal{U}}^{-3}$	$1.8 \times 10^{36} \kappa_e^2 \Lambda_{\mathcal{U}}^{-10/3}$	$1.8 \times 10^{33} \kappa_e^2 \Lambda_{\mathcal{U}}^{-4}$
(c) $\Lambda_{\mathcal{U}} : \gamma\gamma$	$1.0 \times 10^3 \kappa_{\gamma}^{3/4}$	$160 \kappa_{\gamma}^{2/3}$	$33 \kappa_{\gamma}^{3/5}$	$3.1 \kappa_{\gamma}^{1/2}$
(d) $\Lambda_{\mathcal{U}} : e^-e^+$	$125 \kappa_e^{3/4}$	$25 \kappa_e^{2/3}$	$6.8 \kappa_e^{3/5}$	$0.88 \kappa_e^{1/2}$

TABLE II: Volume emissivities of (a) photon-photon and (b) electron-positron annihilation in units of $\text{erg cm}^{-3} \text{ s}^{-1}$, where $\Lambda_{\mathcal{U}}$ has been normalized to 1 TeV, and lower bounds on $\Lambda_{\mathcal{U}}$ in units of TeV from SN1987A for (c) photon-photon and (d) electron-positron annihilation for various values of $d_{\mathcal{U}}$ and a supernova temperature of 30 MeV.

$$Q_e^j = \int \frac{2d^2\vec{k}_1}{(2\pi)^3} \frac{1}{e^{(E_1-\mu_e)/T} + 1} \int \frac{2d^3\vec{k}_2}{(2\pi)^3} \frac{1}{e^{(E_2+\mu_e)/T} + 1} \frac{s(E_1 + E_2)}{2E_1E_2} \sigma_{e^-e^+}^j, \quad (24)$$

where μ_e and $-\mu_e$ are the electron and positron chemical potentials, respectively, and T is the supernova temperature. In the core of a supernova $\mu_e \simeq (3\pi^2 n_e)^{1/3} \simeq 345 \text{ MeV}$. After performing the integration and summing over possible final states, we find the volume emissivity from electron-positron annihilation to tensor unparticles is

$$Q_e = \kappa_e^2 \frac{4^{d_{\mathcal{U}}-1} A_{d_{\mathcal{U}}} I_e(d_{\mathcal{U}})}{8\pi^4 (d_{\mathcal{U}} + 1)} \frac{T^{2d_{\mathcal{U}}+5}}{\Lambda_{\mathcal{U}}^{2d_{\mathcal{U}}}}, \quad (25)$$

where

$$I_e(d_{\mathcal{U}}) = \int dy_1 dy_2 \frac{(y_1 y_2)^{d_{\mathcal{U}}+1} (y_1 + y_2)}{(e^{y_1 - \mu_e/T} + 1)(e^{y_2 + \mu_e/T} + 1)}. \quad (26)$$

For a supernova temperature of 30 MeV, the values of $I_e(d_{\mathcal{U}})$ are 0.41 for $d_{\mathcal{U}} = 4/3$, 0.73 for $d_{\mathcal{U}} = 3/2$, 1.3 for $d_{\mathcal{U}} = 5/3$, and 4.3 for $d_{\mathcal{U}} = 2$.

C. Limits on $\Lambda_{\mathcal{U}}$ and κ

To prevent the neutrino burst from SN1987A from being too short, the upper limit on the supernova volume emissivity of new physics is [64, 73]

$$Q_{SN} \sim 3 \times 10^{33} \text{ erg cm}^{-3} \text{ s}^{-1}. \quad (27)$$

Using this upper bound on the volume emissivities from photon-photon and electron-positron annihilation to tensor unparticles, we obtain limits on $\Lambda_{\mathcal{U}}$ and κ for a supernova temperature of 30 MeV. The results for the volume emissivities and bounds for $d_{\mathcal{U}} = 4/3, 3/2, 5/3$, and 2 are presented in Table II. The bounds from photon-photon annihilation are on the same order as those from the matter density, while the bounds from electron-positron annihilation are an order of magnitude less.

Previous studies have calculated the volume emissivity bounds from nucleon brehmstrahlung for vector unparticles [53, 55, 59] and scalar unparticles [55]. The constraints on vector and scalar unparticle couplings to the standard model from 5th force experiments were also calculated in [55].

The operators under study in Ref. [55] had coefficients $\kappa/M_Z^{d_{\mathcal{U}}+d_{SM}-4}$ instead of $\kappa/\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}+d_{SM}-4}$. Hence, to compare our results we replace $\Lambda_{\mathcal{U}}$ with M_Z and find the constraints on the dimensionless coupling constant, κ . Table III contains the bounds from supernovae volume emissivity and 5th force experiments on parity conserving scalar and vector unparticle and standard model interactions [55], and our bounds on tensor unparticle and standard model interactions.

In [53] it was found that for a vector unparticle coupling to nucleons, data from SN1987A gave the bounds

$$\frac{\kappa}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} (30 \text{ MeV})^{d_{\mathcal{U}}-1} = C_{\mathcal{U}} \frac{\Lambda_{\mathcal{U}}^{d_{BZ}-d_{\mathcal{U}}}}{M_{\mathcal{U}}^{d_{BZ}-1}} (30 \text{ MeV})^{d_{\mathcal{U}}-1} \lesssim 3 \times 10^{-11}, \quad (28)$$

where $d_{SM} = 3$. Again, to compare to the results in [55] we replace $\Lambda_{\mathcal{U}}$ with M_Z . These results are presented in Table III.

As can be seen in Table III, our bounds for tensor unparticle and standard model couplings are weaker than those for vector unparticle and standard model couplings [53, 55]. Our results are weaker than the fifth force experiment bounds on scalar unparticle couplings for $d_{\mathcal{U}} = 4/3$ and $5/3$, and on the same order of magnitude for $d_{\mathcal{U}} = 2$ [55]. The tensor unparticle bounds are on the same order of magnitude as the supernovae volume emissivity bounds on scalar unparticle couplings [55].

$d_{\mathcal{U}}$	4/3	3/2	5/3	2
Tensor Unparticles				
Unparticle Density	1.7×10^{-6}	1.1×10^{-5}	7.9×10^{-5}	4.4×10^{-3}
SN1987A: $\gamma\gamma$	3.8×10^{-6}	1.4×10^{-5}	5.2×10^{-5}	8.7×10^{-4}
SN1987A: e^-e^+	6.6×10^{-5}	2.2×10^{-4}	7.6×10^{-4}	1.1×10^{-2}
Vector Unparticles				
5th force[55]	1.4×10^{-15}	—	1.8×10^{-10}	2×10^{-5}
SN1987A[55]	3.5×10^{-8}	—	1×10^{-6}	3×10^{-5}
SN1987A[53]	4.3×10^{-10}	1.7×10^{-9}	6.3×10^{-9}	9.1×10^{-8}
Scalar Unparticles				
5th force[55]	1.2×10^{-13}	—	1.6×10^{-8}	1.7×10^{-3}
SN1987A[55]	2.4×10^{-6}	—	6.6×10^{-5}	2×10^{-3}

TABLE III: Comparison of upper bounds on the coupling constant κ from tensor unparticle density, supernovae volume energy loss rates for scalar [55], vector [53, 55], and tensor unparticles, and fifth force experiments for vector and scalar unparticles [55]. The conformal scale $\Lambda_{\mathcal{U}}$ is taken to be M_Z . Entries with dashes are not available

V. CONCLUSION

We calculated the present day density of tensor unparticles from photon-photon and neutrino-neutrino annihilation and the supernovae volume energy loss rates from photon-photon and electron-positron annihilation to tensor unparticles. The deconstruction of the unparticle given in [61] was used to calculate these observables.

Using the matter density of the universe as an upper bound on the present day tensor unparticle density, we placed constraints on the conformal scale $\Lambda_{\mathcal{U}}$ and the dimensionless coupling constant $\kappa_{\gamma} = \kappa_{\nu} = \kappa$. The supernovae volume emissivity bounds on new physics from SN1987A were used to place bounds on $\Lambda_{\mathcal{U}}$ and the individual coupling constants between tensor unparticles and photons, κ_{γ} , and tensor unparticles and electrons, κ_e .

Bounds for supernovae volume emissivities from electron-positron annihilation were an order of magnitude less than those from tensor unparticle density and supernovae volume emissivity from photon-photon annihilation to tensor unparticles. The bounds on the di-

dimensionless coupling constants and $\Lambda_{\mathcal{U}}$ decreased as $d_{\mathcal{U}}$ increased. Taking $\Lambda_{\mathcal{U}} = 1$ TeV and assuming that all the dimensionless coupling constants are equal, the most stringent bounds we found were

$$\kappa < \begin{cases} 4.3 \times 10^{-5} & \text{for } d_{\mathcal{U}} = 4/3 \\ 4.1 \times 10^{-4} & \text{for } d_{\mathcal{U}} = 3/2 \\ 2.9 \times 10^{-4} & \text{for } d_{\mathcal{U}} = 5/3 \\ 1.0 \times 10^{-1} & \text{for } d_{\mathcal{U}} = 2 \end{cases} \quad (29)$$

These bounds are weaker than those found from supernovae volume emissivities [53, 55] and fifth force experiments [55] for vector unparticles. For $d_{\mathcal{U}} < 2$, the constraints for tensor unparticles are weaker than the 5th force bounds for scalar unparticles, but for $d_{\mathcal{U}} = 2$ they are on the same order of magnitude [55]. Our bounds for tensor unparticles are on the same order of magnitude as the supernovae volume energy loss rate bounds for scalar unparticles [55].

The collider phenomenology of tensor unparticles at the LHC and electron positron-colliders has been studied previously [24, 41, 49]. Their results for tensor unparticles at electron positron and hadron colliders were found for $\Lambda_{\mathcal{U}} \leq 1$ TeV and $\kappa = 1$. Our results from cosmological and astrophysical constraints show that the value of κ is bounded by at least one order of magnitude lower for $d_{\mathcal{U}} = 2$ and at least 5 orders of magnitude lower for $d_{\mathcal{U}} = 4/3$, making signals at future colliders more difficult to observe.

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